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FROM TURING TO GIBSON: IMPLICATIONS OF AFFORDANCES FOR THE SCIENCES OF ORGANISMS

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ABSTRACT

We analyze the concept of "affordance" in ecological psychology and the concept of "Turing machine" drawn from computation. We propose that Turing's theory of computation supports Gibson's ecological theory of affordances as entities perceived directly—without invoking representations—as the configurations of Turing machines. Our arguments draw on the compelling reinterpretation of the Turing machine by Andrew Wells. Further, we link affordances with the discovery by Graziano and colleagues of ethological action maps in the motor cortex, which can be understood as neurophysiological attunement to affordances. Thus, affordances and the accompanying theory of direct perception are compatible with the contemporary understanding of the organization of the mammalian brain and with the contemporary understanding of computation by an active agent without recourse to representation. The concept of affordance can provide a powerful guide for work linking neural functioning with organismal behavior.

Glossary

Affordance: An affordance is a potential for action that an object or environment offers to an organism.

Cascade: A [hydrodynamic] cascade model is a theoretical framework used in fluid dynamics to describe the transfer of energy from large-scale motions to smaller scales through a series of interconnected turbulent eddies or vortices, leading to a cascade-like effect.

Criticality: A state or condition in complex systems with a delicate balance between order and chaos, characterized by emergent properties, sensitivity to initial conditions, and self-organized critical phenomena.

Direct perception: A continuous, direct process of detection or "picking up" of sensory information by the perceptual system and obtaining meaning from this information without complex cognitive processing or inference. Direct perception theory emphasizes active engagement with the world rather than passive interpretation of sensory data. It challenges the idea that perception depends upon creating internal representations or mental models.

Instability: A phenomenon in which a small disturbance or perturbation in a system triggers a chain reaction of progressively increasing and heterogeneous disturbances or failures.

Neural attunement: A process that entails synchronizing and aligning neuronal responses across brains (following a shared experience) or within regions of a single brain, such as firing patterns or oscillatory rhythms.

Turing machine: An abstract machine with discrete cells on an infinite tape that can each hold a symbol from a limited set. The machine's memory is stored on this tape. Thanks to its read-write head, the Turing machine can move along the tape while reading and writing symbols on the cells. The head can travel left or right along the tape, inscribe a new sign, and look at the symbol in its current location. The machine behaves in accordance with a set of guidelines referred to as a "transition function." The transition function specifies the action the machine should take based on the symbol it reads and its current state. Consequently, the machine can modify its internal state, write a new symbol on the tape, and adjust the head's movement left or right, all as the transition function dictates. The British mathematician and logician Alan Turing developed the Turing machine, a potent mathematical representation of a computer, in 1936.

What do we understand by the term *affordance*?

Affordances, as conceived by James J. Gibson, are the potential for actions that an object or environment offers to an organism; they are the directly perceived opportunities for interaction or engagement with the surroundings relative to the organism's action capabilities, intentions, and needs. Affordances determine what an organism can do in a given environmental setting and so determine the significance or meaning of that setting for the organism. In this view, then, perception is both non-inferential and intimately linked to action: via their constant and ongoing activity, organisms generate information from their surroundings and use this to guide further action, and they discover meaning through their ongoing exploratory activity, rather than meaning being added to the stimulus by an internal cognitive process (Gibson, 1979). Perception is thus an active process of "keeping in touch with the environment" (Gibson 1979, p. 239), not any mental state in the head.

The theory of **direct perception** of affordances (and therefore, the rejection of "mental gymnastics;" Chemero (2009) has profound implications for mind science—it conflicts with the prevalent metaphors of the "brain as a computer," "perception as sensory input," and "cognition as information processing," leading to "action (behavior) as output." These information-theoretic metaphors invoke representations (processes, or computations, occurring entirely within the nervous system) to mediate organisms' interactions with their environments. These ideas trace back to John von Neumann, who developed the ENIAC (Electronic Numerical Integrator and Computer) in the late 1940s. von Neumann's visionary design encompassed the foundational elements found in modern computers: a central processing unit, main memory, peripherals, and external storage, drawing parallels between this computational architecture and the intricate workings of the brain. According to von Neumann, the CPU mirrored associative neurons, while input and output devices functioned like sensory and motor neurons. This influential "von Neumann architecture" shaped the trajectory of artificial intelligence, and his language has formed the bedrock of our metaphors of the computational architecture of the mind.

von Neumann drew on the work of Alan Turing, the acclaimed mathematician and "father" of computer science. Turing revolutionized computing with his concept of (so-called) **Turing machines**, which he first set out in the 1930s (Turing et al., 1936; Turing, 1950). During the First and Second World Wars, "computers" were not machines but people charged with generating map grids, surveying aids, and navigation and artillery tables based on strictly set rules. Turing aimed to automate this laborious computational process to increase efficiency. He sought to create a machine that could perform calculations like a human computer using paper and pencil. Therefore, the abstract machine he developed was an effort to encompass the overall environment in which human computers undertook their tasks. The moveable head of the machine represented the person, and the infinite paper tape that served as a medium for reading and printing symbols represented the paper and pencil on which the human-computer worked out their sums. The movable head of the machine would thus traverse the tape, allowing for the manipulation of symbols.

Turing's aim here was entirely practical and mathematical, not psychological: his goal was to automatize calculation, not provide a comprehensive analysis of human behavior or cognition. However, his ideas inspired speculation that human thought might operate algorithmically like a universal Turing machine that can simulate an arbitrary Turing machine on arbitrary input. Thus, von Neuman and others developed the metaphor of the brain as a universal Turing machine, which opened doors for modeling cognition with algorithm-dependent digital computers. However, as Andrew Wells points out in his book *Rethinking Cognitive Computation: Turing and the Science of the Mind* (Wells, 2017), the development of these ideas included a crucial misstep, whereby the Turing machine's symbol manipulations were reconceived as a model of internal brain-based cognitive processes. The paper tape was seen as an analog of human memory. That is, early proponents of a computational approach to mind placed the entire Turing machine into the head of the human-computer, whereas, as we have made clear above, the infinite tape (representing ample paper) and the

symbols manipulated by a Turing machine (representing the calculations made on the paper) are both external to the mind and part of the environment. Even the machine-head is not to be seen as a model of the mind alone but of the entire person, equipped with paper and pencil, operating in the environment (Wells refers to this set-up as a "mini-mind" to get across the idea that this could be a complete description of an agent with a very simple mind, or a partial description of a more complex one). Turing machines are thus ecological contraptions in a Gibsonian sense—calculations result from an interaction between the agent (person) and the environment (paper and pencil), and the manipulated symbols sit outside the mind and are not part of it.

The mistaken conceptualization of Turing machines as "inside the head" inevitably (and fatally) minimized the role of bodies and the environment in cognition, enabling the belief that computer intelligence could rival human intelligence despite lacking a physical embodiment. In this computational viewpoint, psychological processes became associated with "information processing." Sensory input entered the cognitive system, symbols were manipulated as in a computer, and the output of these cognitive computations guided actions. This conception casts perception, cognition, and action as separate, sequential processes. Understanding the mind now centered on the processing between input and output, with the brain being considered hardware and cognitive processes as software.

It is crucial to delve into the history of, and subsequent misconception surrounding, the universal Turing machine to better understand how the theory of affordances (and direct perception, more generally) aligns with the biology of the body, including the nervous system and avoids the intractability of information-theoretic metaphors of neural function. For instance, the brain operates at multiple levels of organization, from individual neurons to neural networks, brain regions, and global dynamics. Each level has unique physiological properties, which makes it challenging to find a unified information-theoretic framework. Information-theoretic measures rely on assumptions about information representation and interpretation, but these assumptions may not capture the complexity and fluidity of neural processing. Finally, the brain is dynamic and functions in a context-dependent manner; that is, it handles information based on the system's state and goals. Information theory models, in contrast, are static, which is a strong limitation of these models. Hence, the information-theoretic interpretation of the Turing machine is of limited value in understanding the organization and role of the nervous system and how an organism engages with its surroundings.

A more accurate understanding of Turing machines as systems comprising an agent embedded in an environment makes a more ecological view of cognitive computation possible. It potentially reconciles what would appear to be incommensurate paradigms (Barrett, 2011). Specifically, Wells (2002, 2017) proposes that if we combine Gibson's theory with Turing's computational theory, generating a formal model of affordances as configurations of a Turing machine becomes possible. The integration of Turing's and Gibson's theories undercuts the isolated "brain as a computer" metaphor by bringing to the fore the complementary relationship between internal organism structure and external environmental structure (Wells, 2002, 2017).

This treatment of affordances make them facts of the environment (the tape and symbols = environment and ambient energy arrays), the behavior (movements of the machine's head = movements of the organism), and the environment and the organism determinately linked to ongoing behavior via the organism's capabilities (manipulation of symbols based on the strictly set rules = **neural attunement**). A configuration of a Turing machine is defined by an ordered triple $(x, q, k) \in \Sigma * \times K \times N$, where x represents the symbol on the tape, q represents the machine's current state, and k represents the machine's position on the tape (Turing, 1950). This comprehensive configuration determines the machine's future behavior; effectively predicting the future behavior of the machine hinges solely on taking into account the machine's current state and the symbol on the tape. Hence, the theory of computation, pioneered by Turing, establishes a direct relationship between a symbol, the state of a machine, and the symbol's position on the tape, enabling precise manipulation of that symbol. Similarly, the theory of affordances connects objects' inherent properties to the range of potential actions available to an organism possessing distinct capabilities (Wells, 2002, 2017).

What role does affordance play in perception? Is it the entity organisms perceive or the means through which organisms perceive? Are affordances the only perceptual dependent variables?

We hold that organisms perceive affordances—that is, affordances are perceived entities. This view vitiates "perception through some entity" models. For example, let us assert for argument's sake that organisms perceive affordances through some entity "X." The question immediately following this assertion is: "How is 'X' perceived?" and if one claims that "X" is perceived through another entity "Y," then the question immediately following is: "How is 'Y' perceived?," invoking an intractable sequence of mediators for perception. A logical solution to the impossibility of infinite regress is that perception of affordances is "direct," without any representation or mediating entity "X." The ecological program of research has shown that information in the environment is sufficient to specify affordances directly as the configuration of a Turing machine (coupling the facts of the environment, the organism's behavior, and the link between the organism and the environment). As Gibson noted, "Perhaps the composition and layout of surfaces constitute what they afford. If

so, to perceive them is to perceive what they afford. This is a radical hypothesis because it implies that the 'values' and 'meanings' of things in the environment can be directly perceived" (Gibson, 1979, p. 129). Modern ecological psychologists frequently regard information-as-specification as the main principle of Gibson's ecological philosophy. Consequently, empirical investigations focus on identifying specific energy patterns within the surrounding stimulus array to support the theory of direct perception. Nevertheless, organisms can rely on non-specifying variables in certain circumstances until sufficient perceptual learning occurs to enable a shift to the specifying variables (Fajen, 2005; Jacobs and Michaels, 2002). For example, humans react to looming objects on a collision course with their faces by blinking their eyes as a defensive reaction. In experimental settings, newborns blink their eyes when a looming virtual object reaches a threshold visual angle or angular velocity, strategies that work adequately to blink their eyes in advance of virtual contact so long as the object is not accelerating. By six months, infants have switched to a time-to-contact strategy (used by adults), effective for all looming objects, including those accelerating on approach (Kayed and van der Meer, 2007). Adult novices rely more than experts on task variables lacking specificity in tasks, for instance, in which participants perceive masses of colliding balls based on changes in optical patterns (Jacobs et al., 2000; Runeson, 1988). These anomalies seem to challenge the ecological theory unless one accepts that the specification of information is not central to direct perception (Withagen and Chemero, 2012) and that perceptual learning is a normal part of development and accommodation in animals of all ages, especially among young. In a similar vein, it would be interesting to examine perception and neural organization in amphibians before and after metamorphosis (such as from an aquatic tadpole to an air-breathing frog with four limbs). Metamorphosis entails a wholesale change in body shape and function, diet, locomotion, and more; changes in affordances should accompany such physical and ecological changes and, thus, changes in relevant specifying variables. In this way, newly-metamorphosed frogs can be considered novices with respect to their new bodies and lives. Hence, they are a good target for studies of perceptual attunement to specifying variables (for example, about the movement of mobile prey).

Historically, perception of class membership has been treated as a challenge to direct perception because if classes do not have determinate boundaries and, thus, do not have physical properties in common, then there are no patterns in the ambient light that specify class membership (Withagen and Chemero, 2012). In this situation, a class refers to entities based on family resemblances. Nevertheless, class members cannot always be specified precisely (as in the class of "tree"—the boundary between bush and tree is permeable, and likewise between vine and tree). This challenge rests on the assumption that a linguistic entity (the notion of "class") is also a perceptual entity, meaning it specifies an affordance. This assumption is faulty. Human language results from an inherently constructive process (Arbib et al., 2023). While language can refer to affordances, such as asking one to report if one can step over a barrier or will need a ladder, we should not assume that all linguistic constructions refer transparently to affordances nor that all affordances are accessible to language. Experimental procedures that require participants to use linguistic constructs (such as the notion of class membership) to frame their responses to experimenters' queries add a layer of translation on top of perception; such procedures ask about information removed from affordances. Thus, direct perception of class membership should not be expected. In our view, the historical conundrum of perception of class membership by direct perception can be considered irrelevant to evaluating the validity of the theory of direct perception.

In summary, perception is intricately tied to the organism's precise location and cannot be separated from it. This reality undermines the concept of perception mediated by external entities, suggesting instead that perception is direct and centered on affordances. Although challenges to the theory of direct perception arise, such as reliance on non-specific variables or, historically, identifying members of a class, a broader understanding of information and the relation between perception and language enables one to handle these challenges as compatible with direct perception.

Why is affordance any better than stimulus? What does a theory of affordance suggest that stimuli cannot; how has it moved the needle past Gibson 1960's recognition of how little we can define stimuli?

A *stimulus* refers to a physical event or object that can stimulate our senses by transducing energy (chemical, electromagnetic, or mechanical) via the sensory receptors into electrochemical transduction through neurons. A stimulus exists independently of an organism's abilities or intentions. Conversely, *affordance* refers to the arrangement of stimuli in structured patterns that delineate an organism's potential to interact with its environment to pursue its objectives (Heft, 2017, 2018). They depend on the relationship between the organism's abilities and intentions and the properties of the environment. Affordances are context-dependent and relative to the organism's capabilities and needs. For instance, an apple affords grasping and eating, a certain noise affords covering the ears or to investigating its source, and sunlight affords basking or adjusting one's position for more warmth. To summarize, stimuli impose discrete sensory inputs on organisms, while affordances are perceptions of opportunities for action based on an organism's abilities and intentions. Affordances go beyond the stimulation of sensory receptors and involve the organism's potential environmental engagement. Gibson showed that organisms could not simply rely on properties of light defined by

classical physics and geometry as relevant descriptors for biological vision. Instead, they must turn to the global patterns of stimulation to which organisms have become attuned through both evolution and development. It is also worth noting that, as Gibson (1976) pointed out, animals in their natural environments encounter a "flowing sea of stimulus energy" (p. 398) to which organisms have become finely attuned through evolution and from which animals can generate information for their use; only in the laboratory can we impose discrete stimuli that target particular sensory receptors in isolation.

How does the organization of the central nervous system support the perception of affordances? The pioneering work of Michael Graziano offers one answer to this question. In 2002, Graziano and colleagues discovered that the motor cortex of rhesus monkeys exhibited an arrangement distinct from that previously known: namely, functional zones linked to various action categories (Graziano et al., 2002), which they referred to as "ethological action maps." The theological action map encompassed a range of complex, functionally- relevant actions, including hand-to-mouth movements, defensive movements safeguarding the body, reaching and grasping motions, and other behaviors typical of macaques. The research team could elicit these complex and well-coordinated behaviors by applying electrical stimulation to specific regions within the cortical action zones. These ethological action maps in rhesus monkeys have thus challenged conventional understandings of the motor cortex (Graziano, 2006; Graziano and Aflalo, 2007; Graziano, 2016). Since these initial studies, Graziano and colleagues have substantiated these findings using various methodologies such as electrical and optogenetic stimulation, chemical manipulation, lesions, single neuron recording, functional imaging, anatomical tract tracing, behavioral analysis, and computational modeling (Aflalo and Graziano, 2006a,b, 2007; Cooke et al., 2003; Cooke and Graziano, 2003, 2004a,b; Graziano et al., 2004a,b; Graziano and Cooke, 2006). Furthermore, ethological action maps have been investigated in rhesus monkeys by others (Overduin et al., 2012), and extensively in other species, including rats (Brecht et al., 2004; Brown and Teskey, 2014), mice (Harrison et al., 2012), galagos (Stepniewska et al., 2005, 2009, 2011), squirrels (Cooke et al., 2012), cats (Ethier et al., 2006), and humans (Desmurget et al., 2014). Such work suggests that the ethological action map may be a fundamental organizing principle within the motor cortex of mammalian species. This, in turn, has profound implications for comprehending the neural basis of perceiving and acting upon affordances.

On the one hand, stimulus-induced rhythmic movements, such as chewing or whisking observed in mice and rats, involve the active engagement of subcortical structures, like the facial nucleus (Berg and Kleinfeld, 2003; Deschênes et al., 2012). On the other hand, actions like reaching or bringing the hand to the mouth prioritize the coordinated activation of multiple muscles simultaneously rather than relying on precise temporal sequencing. These latter movements exhibit a higher degree of flexibility regarding the contribution of individual muscles or joints, while the overall movement remains relatively consistent. Moreover, particular actions can be realized in multiple ways; that is, different combinations of muscles can produce similar functional outcomes (d'Avella et al., 2003; d'Avella and Bizzi, 2005). These findings have led to the intriguing suggestion that perception and action operate at the level of synergies (Cuadra and Latash, 2019; Profeta and Turvey, 2018; Turvey, 2007). In light of these developments, the integration of behavioral research with neuroscience has emerged as an increasingly pressing need, as highlighted by recent calls in neuroscience and the broader field of mind sciences (Krakauer et al., 2017; Parada and Rossi, 2018; Tytell et al., 2011). In this context, affordances, as bridges between perception and action, offer a more promising path toward this objective than a stimulus-centric view of perception.

What is the connection between affordances, behavioral scale, and intention? How distant or reluctant can a perceiving-acting system be before affordances come into play? Do affordances exert their role only when the system is close or willing enough?

Concepts of affordances, behavioral scale, and intention are reciprocally related. Affordances offer individuals potential actions. The individual's behavioral scale, representing the range of actions they can undertake, impacts how they perceive affordances. Intention influences the perception and utilization of affordances. If an object affords myriad behaviors, affordances do not constrain behavior. The multiplicity of affordances associated with an object in a given setting is entirely consistent with the theme of intentionality central to the ecological approach, as noted by Heft (1989): "the affordances of an object are realized in relation to some intentional act in the individual's behavior repertoire" (p. 21).

Organisms are nonfractionable wholes, comprising genes, cells, organs, and limbs, and therefore, explanations for organismal behaviors must align with the scale at which those behaviors emerge—at the ecological level at which organisms perceive and act (Gibson, 1979). Examples for humans include body-scaled ratios, which define the "step-on-ability" of stairs by establishing relationships between leg lengths, eye heights, and riser heights (Konczak et al., 1992; Warren, 1984; Warren and Whang, 1987). It is also the case that while affordances and behavioral scales may align, intention can span scales of space and time that are not necessarily relevant at the ecological level. For example, an

apple affords grasping and eating to an individual with a low blood glucose level but may not be perceived as such by a satiated individual. Likewise, the same apple may afford grasping to an individual who is not hungry but wishes to take it along for an upcoming road trip. The physiological processes observed in these examples thus extend to the scale of metabolism. At the same time, we also have to be aware of the potential influence of intentional long-term planning behavior (i.e., the acquisition of an affordance broadens the range of internal states, enhancing behavioral capabilities across extended time scales). The far-reaching and influential effect of intention spanning multiple scales of space and time is most notably observed in developing organisms, as in human infants who persist in walking despite the costs of unsteady steps, frequent falls, and challenges in perceiving affordances in their newfound upright posture, and as their bodies are changing rapidly, altering affordances on a daily basis (Adolph, 2008; Adolph and Tamis-LeMonda, 2014). Confining affordances to a limited range of space and time scales would undermine the attainment of a comprehensive and systematic explanation of the connections among affordances, behavioral scale, and intention.

How do systems engage with affordances as they move amongst tasks and intentions?

Returning to Wells' ecological computation model, it is apparent that internal states, functioning as components of Turing machines, actively direct attention to the dynamics of the environment (Wells, 2002, 2017). This phenomenon becomes apparent as different configurations gain prominence while the machine moves along the tape during computation. Just as locomotion across the tape is vital for Turing machines, movement through the environment is fundamental to organisms' perception of their environments. However, this requirement does not necessitate an explicit model of the environment within the "brains" of Turing machines or organisms' brains. As we noted above, in an ecological view, perception is the activity by which organisms keep in touch with their environments, not the means by which they construct them. The analogy here is resonating with, or tuning into, the environment; rather than a linear process by which organisms sense, represent, plan, and act, we have a loopy process of ongoing and continual sensorimotor coordination in which the brain and nervous system help ensure appropriate behavior in specific environmental contexts. That is, as Gibson pointed out: "The theory of affordances implies that to see things is to see how to get about among them and what to do or not do with them. If this is true, visual perception serves behavior, and perception controls behavior" (Gibson, 1979, p. 223).

The discoveries regarding the primacy of movement in affordance perception go beyond establishing a connection between an object's physical attributes, such as rotational inertia, and perceptual experiences through manipulating objects in hand, like perceiving heaviness and length-related affordances (Turvey and Carello, 2011). Through skillful navigation of their intentions, human participants can obtain a wide range of information from the same physical events involving grasping and manipulating an object. For example, they can perceive a handheld object's length, width, and shape from the same exploratory motion with that object (Burton et al., 1990; Mangalam et al., 2019a, 2020c; Turvey et al., 1998). They can also adapt their approach to suit specific aspects of their surrounding environment. For instance, they can perceive the length of a handheld object by probing a distant surface and the distance of that surface (Carello et al., 1992). Furthermore, different exploration methods reveal distinct information, such as static moment vs. rotational inertia (Kingma et al., 2004). Notably, the intention behind these exploratory movements shapes their execution. In one study, participants wielded unseen, rectangular parallelepipeds of various sizes and made judgments about their length or width. With feedback, participants gradually shifted their attention towards the optimal variable, demonstrating the education of attention (also known as perceptual learning). When asked to report a new property, participants made significant attentional adjustments that helped place their judgments in the ballpark of the optimal variable for the new property (Arzamarski et al., 2010). Similarly, visual feedback influences judgments of object length by wielding in the hand, leading to refined exploratory movements and the utilization of informative variables in alignment with the received feedback (Michaels et al., 2008; Wagman et al., 2008). Despite the fact that all these studies used a standard set of objects, participants used variable exploratory movements to perceive different affordances of those objects.

Turing's influence extends beyond the logical prowess of Turing machines. The symbols in a Turing machine reflect rate-independent processes (Pattee, 2001). This kind of "rate-independence" means that the symbols persist even during interruptions and reappearances on the screen or page. However, the utility of symbols and logic depends on the support of physics for processing and interpreting logical constraints. At a smaller scale, electrons facilitate digit processes in computers, while at a larger scale, movements (such as keypresses and scrolls) contribute to our comprehension and meaning extraction from computers. Specifically, the usefulness of digitally displayed symbols emerges in conjunction with rate-dependent dynamic elements, such as electric currents and force fields, which sustain the path of these symbols (Pattee, 2013). To understand how these rate-dependent processes complement logic, Turing introduced another, albeit less widely recognized, concept to the behavioral and cognitive sciences realm—the notion of "**cascades**" (Kelty-Stephen and Mangalam, 2022)—a theoretical framework used in fluid dynamics to describe the transfer of energy from large-scale motions to smaller scales, leading to a cascade-like effect.

Turing astutely recognized the role of **instability** in biological pattern formation, exemplified by the striking "rosette" spots on a jaguar, and he underscored its significance in fostering creative and intelligent thinking (Turing, 1952). While some interpretations separate Turing's focus on pattern formation from his development of logical machinery to mimic intelligence (Dawes, 2016), we propose that both domains of thought were integral to his outlook. Recent research argues that Turing's concept of cascading instability aligns with a geometric framework governed by power laws (Kelty-Stephen and Mangalam, 2022). Applying these geometrical frameworks to neuronal activity data has revealed that the brain operates in a state of **criticality**, a state or condition in complex systems with a delicate balance between order and chaos. Rather than resembling random fluctuations occurring independently, cortical columns generate spreading activity extending between neurons and large-scale resting-state networks, operating simultaneously across multiple scales. Applying the same geometric framework to behavioral data has revealed that cascade instability manifests in various aspects of perceptual functioning, including executive functioning, postural control, and effortful perception (Kelty-Stephen and Mangalam, 2022). This perspective emphasizes the complex multiscale patterning of physiological activity that enables the attunement of organisms' perceptual systems with environmental information.

The Turing machine model illustrates that organismal structure complements environmental structure. Nevertheless, sufficient environmental structure for unambiguous perception does not negate the necessity and use of internal structure to facilitate perception and drive behavior. Hence, whether a particular behavior arises from the environmental or organismal structure cannot be determined *a priori*. We have operated under this assumption to investigate how movements support the haptic perception of object properties through wielding an object in hand. In this case, it seems reasonable to narrow our focus to the point of contact (e.g., mechanoreceptors in the skin). However, we must exercise caution to avoid becoming excessively fixated on these experimental details to the extent that we neglect the broader context. Perception entails information beyond the hand alone; it permeates the entire organism, originating from and influencing other areas. It is a holistic reaction that encompasses the entire body. By occluding the grasped object, we do not isolate distinct perceptual subsystems (e.g., visual and haptic); instead, we disrupt a comprehensive cascade encompassing various motor functions. Intriguingly, when participants, blindfolded and standing on a force plate, employ hand movements to perceive properties of an object haptically, the temporal structure of their postural center of pressure (CoP) predicts their judgments of object heaviness and length (Mangalam et al., 2020c; Mangalam and Kelty-Stephen, 2020). Despite the object being held in the hand and not underfoot, the relationship between the feet and the ground surface influences the effortful touch of the hand. Even in cases where the participant remains stationary, the temporal structure of the CoP holds direct implications for perceiving objects supported by the shoulders, with differences arising depending on whether the person focuses on the entire object or just a part of it (Palatinus et al., 2013, 2014). These findings invite contemplation of the intriguing connection between the grasping hand and the standing feet. Similarly, bearded capuchin monkeys, standing bipedally and using stones weighing half their body mass or more to strike palm nuts placed on stone anvils, show more stringent control of the position of their feet and lower legs during their strike than of the hands and arms (Mangalam et al., 2018a,b). Maintenance of postural stability is likely an organizing factor in much human activity, evident in what we term "suprapostural dexterity" (Kelty-Stephen et al., 2021).

Meticulous investigations conducted by Mangalam, Kelty-Stephen, and colleagues have uncovered the significant role played by various physiological manifestations spread throughout the body in perceiving the affordances of handheld objects. Notably, the observed interactions across different scales during hand-wielding, stemming from muscular activity, have proven to be more predictive of perceived length than the measurement of muscular activity alone (Mangalam et al., 2019a,b). Additionally, participants' heads display subtle yet cascading swaying movements that critically impact their ability to integrate visual feedback (Kelty-Stephen and Dixon, 2014). These findings impel us to adopt a swarm perspective when considering the relevance of postural sway in hand-wielding—considering the body to be a veritable swarm of quasi-autonomous parts falling in and out of cooperation (Kelty-Stephen and Mangalam, 2022). Assuming that effortful perception solely revolves around the hand's exploration of an object leads to the assumption that other anatomical parts do not provide any additional valuable information except for downstream harmonics generated by the resonance of hand-wielding throughout the body. However, our previous examination of pairs or triples involving the head, hand, and torso has now expanded to encompass the entire body's movement (Mangalam et al., 2020a,b). The wielded object and arm interact across scales, mutually enhancing each other's contribution. These movement patterns propagate from the forearm to the object and vice versa, influencing the upper arm. Moreover, beyond these interconnected relationships within the upper body, an increase in multifractality within the postural CoP predicts subsequent improvements in perceptual accuracy. These findings collectively exemplify why it is crucial to envision the body-object complex as constantly adapting its configuration, akin to a Turing machine as conceived ecologically, and to consider the waxing and waning of cascading movement patterns implied by Turing's cascade instability to facilitate the perception of affordances.

Turing's profound insights into both theoretical Turing machines (Turing, 1950) and cascade instability in physical systems (Turing, 1952) provide valuable lessons for comprehending the interplay between logical and physical processes

that underlie organism behavior. Turing's analysis suggests that the interpretation of symbols and logic heavily relies on the support provided by physical processes. The interdependence of logical and physical processes is evident through cascading dynamics, as demonstrated by empirical findings in various domains of perceptual functioning, such as executive functioning, postural control, and effortful perception (Kelty-Stephen and Mangalam, 2022). This perspective highlights the inseparable relationship between the [logical] event of arriving at a perceptual judgment and the [physical] process of arriving at that judgment. Further exploration into the role of cascade instability in organizing the complex dynamics of neuronal activity underlying the perception of affordances holds great promise. Empirical inquiries into these cascading mechanisms will yield novel insights into how organisms engage with affordances as they navigate tasks and intentions. By investigating the intricate interplay between physical and cognitive processes, we can deepen our understanding of how organisms perceive and interact with their environment dynamically and adaptively.

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